DEEP IMPACT: MISSION DESIGN APPROACH FOR A NEW DISCOVERY MISSION

William H. Blume
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

ABSTRACT Deep Impact is a new NASA Discovery mission to launch in early 2004. This paper discusses the mission design strategies for this unique mission, which will target a 500-kg impactor into a comet nucleus at a speed of 10 km/s, in order to reveal the subsurface materials and structure. Trajectory designs are shown for reaching comet P/Tempel 1 near perihelion at its 2005 apparition and for the approach and flyby trajectories of the flyby spacecraft, which carries the impactor up to 24 hours before impact. The mission and encounter timelines are discussed for the events of the cruise, approach, and encounter phases of the mission, including the strategies for observing the impact and returning the data to Earth.

MISSION OVERVIEW

Deep Impact was selected in July 1999 to be the eighth mission in NASA's Discovery program. The mission's purpose is to conduct a scientific cratering experiment on the nucleus of comet P/Tempel 1 near the time of perihelion for its 2005 apparition. This will be accomplished by launching two joined spacecraft (flyby spacecraft + impactor) in January 2004 to approach the comet in early July 2005 at a speed of about 10 km/s. Figure 1 shows the spacecraft and instrument components. The impactor, a battery-powered spacecraft with a dry mass of 500 kg, will observe the approaching nucleus with an optical camera and maneuver itself to a collision course toward the lighted portion of the nucleus. After separation from the impactor, the flyby spacecraft will do a maneuver to delay and deflect its flight path toward the nucleus so that it can observe the impact, ejecta, crater development, and crater interior during a 500-km flyby of the nucleus that occurs about 17 minutes after the impact. The flyby spacecraft carries a remote sensing payload of two combined instruments for imaging and infrared spectroscopy. Close-in observations of the nucleus by the impactor camera will be sent to the flyby spacecraft by a radio link in the last hour before impact.

Figure 1 Deep Impact Spacecraft and Instrument Components
(separated for clarity)

The flyby spacecraft will send portions of the scientific and engineering data to the ground during the encounter and record the primary data sets for later playback. Simultaneous observations of the comet before, during, and after the impact will also be conducted from Earth-based observatories as an essential part of the total experiment. All scientific and supporting engineering data will be archived for future use by the scientific community.

TARGET SELECTION

The comet Tempel 1 (officially designated 9P/Tempel 1) is the selected target for the Deep Impact mission based on an excellent fit with the scientific objectives and its accessibility for launches from the Earth at relatively low energy. With an orbital period of 5.5 years and a descending node near its perihelion at 1.5 AU, Tempel 1 can easily be reached for a flyby mission and has excellent Earth-based observability at its 2005 apparition. The trajectory geometry allows a launch mass sufficient for a 500-kg impactor and favorable approach conditions, including the <64° solar phase angle and the desired impact speed >10 km/s to ensure vaporization of the impactor and creation of a suitably large crater. Several other targets, including Tuttle-Giacobini-Kresak, were considered, but Tempel 1 has the best combination of encounter conditions, observability, and accessibility in the time period of interest.

MISSION TRAJECTORY

The January 2004 launch opportunity has been selected as the mission baseline. This opportunity requires an 18-month flight time to reach Tempel 1 in July 2005, including an intermediate Earth flyby one year after launch. Figure 2 shows the interplanetary trajectory for the first launch date of a 20-day launch period beginning January 1, 2004. Table 1 provides values for important trajectory parameters over the 20-day launch window, based on integrated trajectory simulations. The approach phase angle provides good illumination of the target for early acquisition by the high-resolution imager. The one-year, Earth-to-Earth trajectory arc provides valuable time for calibration and testing of the spacecraft, payload, guidance software, and mission operations system, including observations of the Moon at the Earth flyby. A January 2005 direct trajectory is available as a mission backup, but the 2004 opportunity provides the best mission timeline for ensuring encounter readiness, while still completing space operations in only 19 months.With use of the Delta 7925H launch vehicle, the maximum launch energy of 11.82 $(km/s)^2$ on the last day of the launch period results in a launch vehicle capability of 1144 kg for the injected payload, allowing an impactor mass of 500 kg with comfortable mass margins.

A systematic search was made for near-Earth asteroids to be used as calibration targets to test the spacecraft targeting algorithms before arrival at Tempel 1. The one-year, Earth-to-Earth trajectory arc allows flexibility in trading inclination with eccentricity, which could be used either to target a potential calibration target or adjust the approach conditions on return to Earth for calibration measurements of the lunar surface. To date, no near-earth asteroids have been found close enough to the cruise flight path to justify a trajectory adjustment (and the associated increase in propulsion requirements), but new objects continue to be found and will be studied as potential calibration targets in the future. The final Earth-to-Tempel 1 trajectory arc has an orbit period very close to 1.5 years, so the potential for an extended mission, by returning to the Earth for another gravity assist in January 2008, has been recognized and is under study.

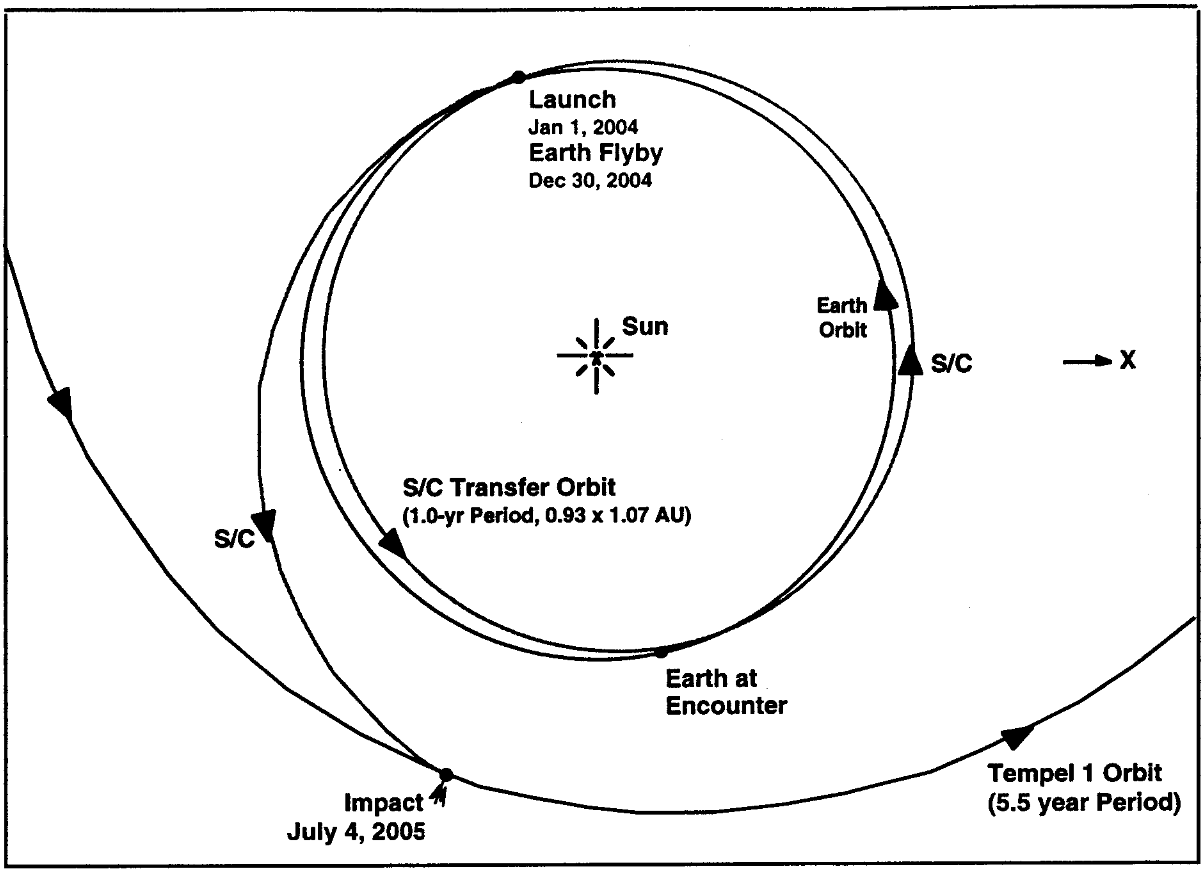


Figure 2 Deep Impact Interplanetary Trajectory

Table 1 Deep Impact Trajectory Parameters for 2004 Opportunity.

Trajectory Parameter	Open	Middle	Close
Launch (L)			
Launch Date	1-1-04	1-11-04	1-21-04
Launch Energy $(km/s)^2$	11.71	10.94	11.82
Launch Declination (°)	28.5	28.5	28.5
Launch Mass (kg)	1147	1175	1144
Cruise			
Flight Time (days)	550	540	530
Max. Sun Range* (AU)	1.565	1.565	1.565
Perihelion (AU)	0.927	0.931	0.929
Earth Flyby	12-30-04	1-9-05	1-19-05
Flyby Radius (R_e)	3.26	2.57	1.67
Encounter (E)			
Encounter Date	7-4-05	7-4-05	7-4-05
Approach Speed (km/s)	10.20	10.28	10.37
Approach Phase Angle (°)	63.8	62.9	62.3
Sun Range (AU)	1.506	1.506	1.506
Earth Range (AU)	0.893	0.893	0.893

* to Encounter + 30 days

MISSION TIMELINE

The Deep Impact mission timeline emphasizes a simple profile of activities that can be accomplished by a small mission operations team. As shown in Figure 3, there are three periods of focused operations following launch, near encounter, and near the important navigation event at the Earth flyby, which will also be used for instrument calibration. In the first 30 days after launch, the spacecraft and imaging instruments will be characterized and a first trajectory correction maneuver (TCM) will be executed. Increased DSN coverage for radiometric navigation data is scheduled for the first 30 days after launch, and tracking is then reduced to one 6-hr pass per week for the long intermediate period of cruise to the target. Additional passes (usually once per month) are planned for spacecraft and payload tests, the Earth flyby, and rehearsals for encounter. Except very near the encounter, all tracking coverage will be through the DSN 34-m subnets. The third period of focused operations is from 60 days before, until 1 day after the Tempel 1 encounter. First detection of Tempel 1 from the spacecraft is expected between E-60 and E-30 days, and this will be aided by Earth-based observations. Increased navigation tracking data, including optical data, will be collected for the final Earth-commanded TCMs at E-10 and E-5 days. A final targeting maneuver will be executed shortly before separation of the impactor at E-24 hours. The flyby S/C then executes a braking maneuver to deflect and delay the flyby trajectory and executes a preprogrammed sequence with on-board timing updates to conduct the flyby observations of Tempel 1 and the impact event.

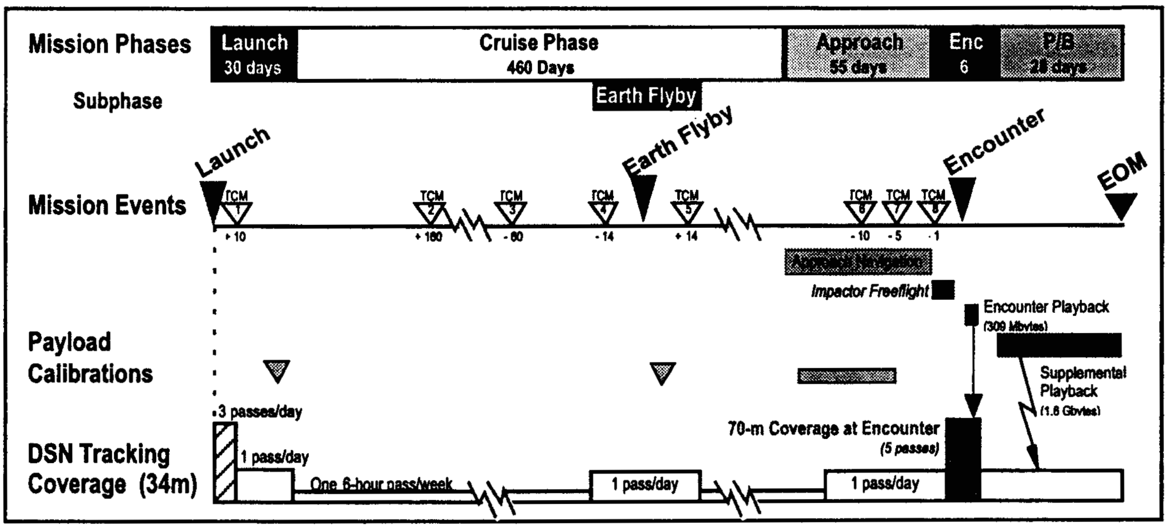
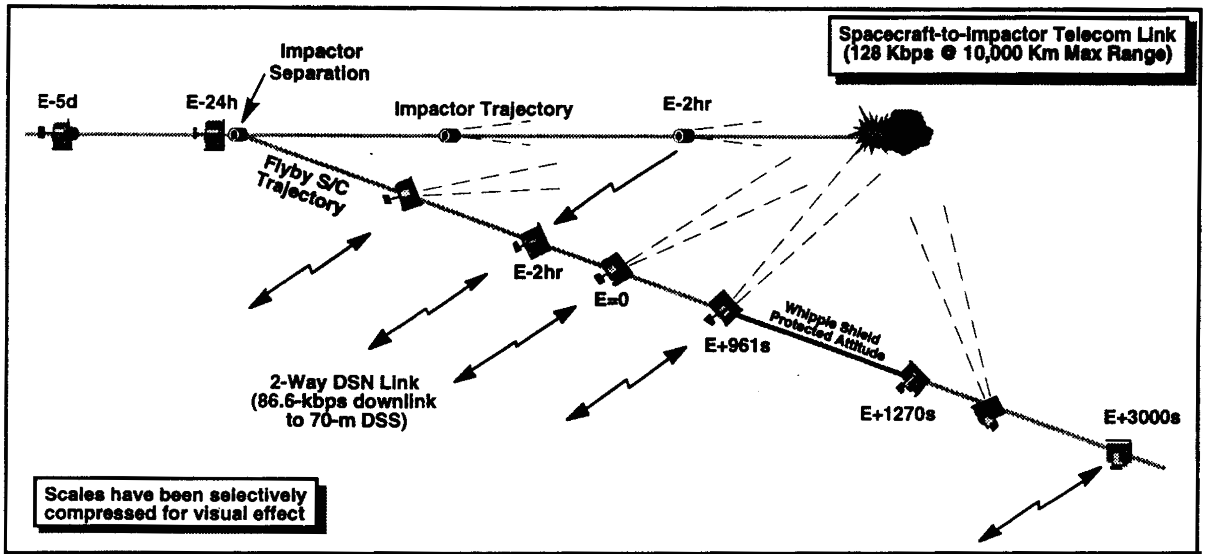


Figure 3 Deep Impact Mission Timeline

ENCOUNTER TIMELINE

The flyby S/C and impactor encounter scenario is described in Figures 4 and 5. The impactor is entirely self-guided after separation at E - 24 hours, but maintains a telemetry link with the spacecraft at 128 kbps until the point of impact. The impactor imaging system provides preselected close-in images of the nucleus surface prior to impact that will be stored and relayed back to Earth in realtime. After separation of the impactor, the flyby S/C performs a deflection maneuver of 120 m/s that delays its closest approach to 1010 sec after impact and targets a 500 km flyby of the nucleus over its South Ecliptic terminator as shown in Figure 6. This facilitates solar array positioning as the spacecraft turns to view the nucleus on approach. Multispectral imaging of the impact event, crater development, the nucleus surface, and the crater interior continue until the spacecraft slew reaches 45° at 50 sec before closest approach. At this point the spacecraft is oriented such that its Whipple shields are positioned to protect the spacecraft from any dust particles as it passes through the inner coma. The spacecraft holds this fixed attitude until 150 sec after crossing the orbital plane. After safe passage through the inner coma the spacecraft resumes imaging of the departing nucleus at high phase angles to observe changes in activity.



E - 5 days	TCM-7 approach maneuver.
E - 30 hours	Impactor checkout, final TCM-8, if required. Impactor to internal power just before separation.
E - 24 hours	Impactor separation at 300 mm/s relative speed. Flyby S/C waits to execute 120-m/s deflection.
E - 2 hours	Impactor radio link at 128 kbps continues to impact. Approach imaging relayed to earth at 86.6 kbps.
E - 60 sec	Flyby S/C begins high-rate imaging to capture impact event and crater development.
E = 0	Impactor contacts nucleus and vaporizes, crater development begins. Flyby S/C range 10,200 km.
E + 600 sec	Flyby S/C begins high-resolution crater observations. Selected images & spectra relayed to Earth.
E + 961 sec	Imaging ends as S/C is oriented for safe crossing of inner coma. Nucleus range is 707 km.
E + 1270 sec	Crossing of inner coma and orbital plane complete, start turn for lookback imaging.
E + 3000 sec	Complete turn back to cruise attitude and start HGA playback of all primary encounter data in memory. 8-hour playback to Goldstone and Canberra 70-m DSS at 86.6 kbps returns 309 Mbytes of data.

Figure 4 Deep Impact Encounter Schematic

Up to 309 Mbytes of primary imaging and spectral data will be recorded in solid-state memory on the flyby S/C, with 8 Gbytes of supplemental data held in a disk recorder. First playback of the primary science data will be completed within 8 hours shortly after the encounter, using the 70-m Goldstone and Canberra tracking antennas and an 86.6-kbps data rate. Portions of the supplemental data, budgeted at 20% of the disk recorder volume, will be selected by the Science Team for return during the four weeks after encounter, using one 8-hour pass per day on a 34 m DSN subnet and a 16-kbps playback rate.

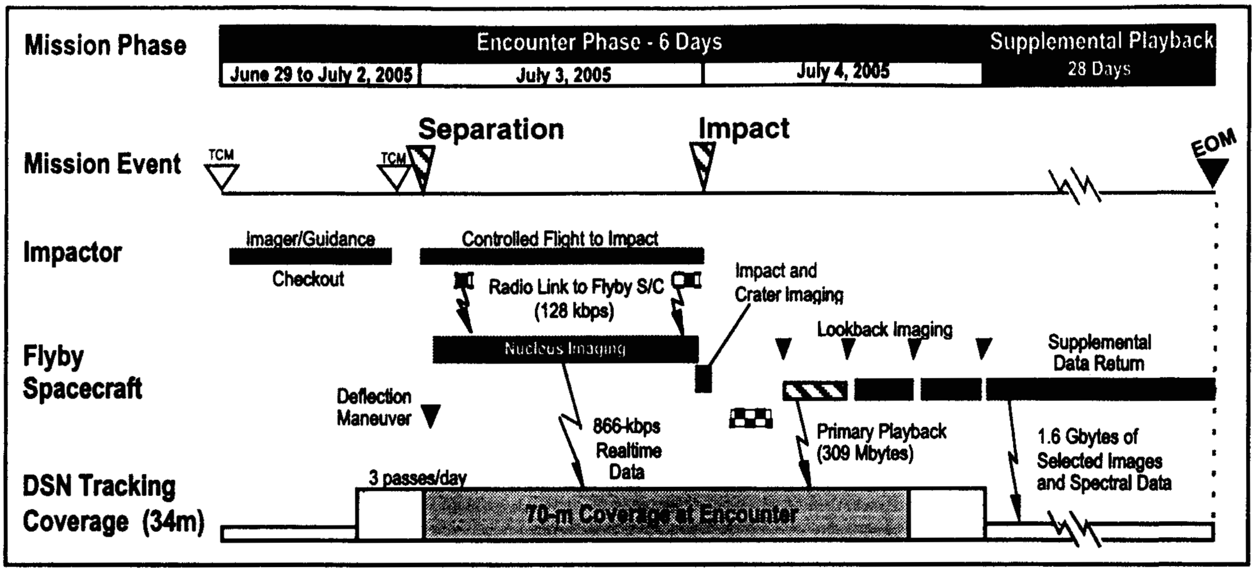


Figure 5 Deep Impact Encounter Timeline

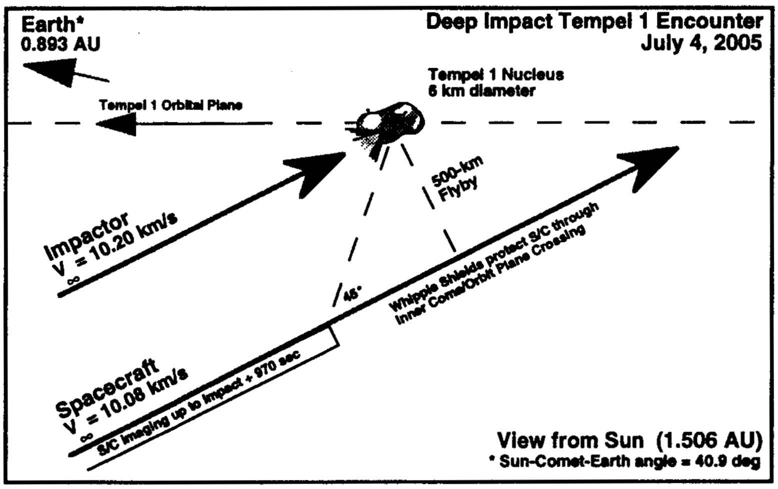


Figure 6 Near-Encounter Trajectory - Sun View

INTERPLANETARY NAVIGATION

Detailed interplanetary navigation studies have been conducted at JPL during the concept study to validate all major requirements and to demonstrate the capability for accurate delivery to the target, including adequate margins in propellant and delivery uncertainties. During the launch, cruise, and approach phases, ground-controlled navigation will deliver the flyby S/C and attached impactor on a very accurate approach trajectory to Tempel 1. A schedule of interplanetary trajectory correction maneuvers (TCMs) has been laid out as shown in the mission timeline. The TCM times relative to launch and encounters are optimized to progressively correct the spacecraft trajectory as knowledge is improved by the processing of tracking and optical data.

After the first TCM, which is used primarily to take out launch vehicle injection errors, smaller maneuvers target the Earth flyby (TCMs 2 to 4) and the approach to Tempel 1 (TCMs 5 to 8). Table 2 shows the estimated magnitudes of the TCMs and an overall mission maneuver budget for the flyby S/C, which includes the post-separation deflection maneuvers. Compared to the flyby S/C maneuver capability of 240 m/s, there is a very substantial margin of 46 m/s. The TCM budget is dominated by a very conservative estimate for correction of the launch vehicle injection errors, based on JPL support of interplanetary navigation for six Delta launches since 1996. This study also identified the need for a trim to the flyby S/C deflection maneuver to achieve the 500 km nucleus flyby to an accuracy of ±50 km. This maneuver is planned at E - 18 hours.

Table 2 Deep Impact Maneuver Budget

Maneuver	Estimated Magnitude
TCM 1	60 m/s
Earth Targeting TCM 2, 3, 4	7 m/s
Tempel 1 Targeting TCM 5, 6, 7, 8	2 m/s
Deflection Maneuver	120 m/s + 5 m/s for worst-case cleanup
Total Mission ΔV (worst case)	194 m/s, reserve in TCM 1 estimate
Flyby S/C Capability	240 m/s
Margin	46 m/s

During the launch and cruise mission phases, conventional radiometric tracking data (2-way Doppler and ranging) will be collected during each scheduled DSN pass and processed to determine the spacecraft ephemeris. The uncertainty in knowledge of the encounter conditions converges through the cruise phase to a few hundred kilometers, which represents, almost entirely, the comet ephemeris uncertainty from Earth-based observations. A much better solution of the Tempel 1 ephemeris is obtained by optical measurements from the spacecraft during the approach phase. Initial acquisition of the comet is expected at E - 60 days and certain by E - 30 days.

ACKNOWLEDGEMENTS

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The Deep Impact mission concept was developed in a close partnership between the Principal Investigator, Dr. Michael A'Hearn, and his Science Team, Ball Aerospace and Technologies Corp. and the Jet Propulsion Laboratory. Alan Delamere and Richard Reinert at Ball Aerospace were key leaders in developing the instrument and spacecraft concepts. Studies of the trajectory options for Deep Impact have been supported by Louis D'Amario, Paul Penzo, Joan Pojman, and Chen-wan Yen. Interplanetary navigation studies were conducted by Mark Guman and Cliff Helfrich. Optical navigation studies were conducted by George Null and supported by Shyam Baskaran, Robert Gaskell, Edward Riedel, and Stephen Synnott. Impactor guidance studies at Ball Aerospace were conducted by Douglas Wiemer.